Beyond WMAP

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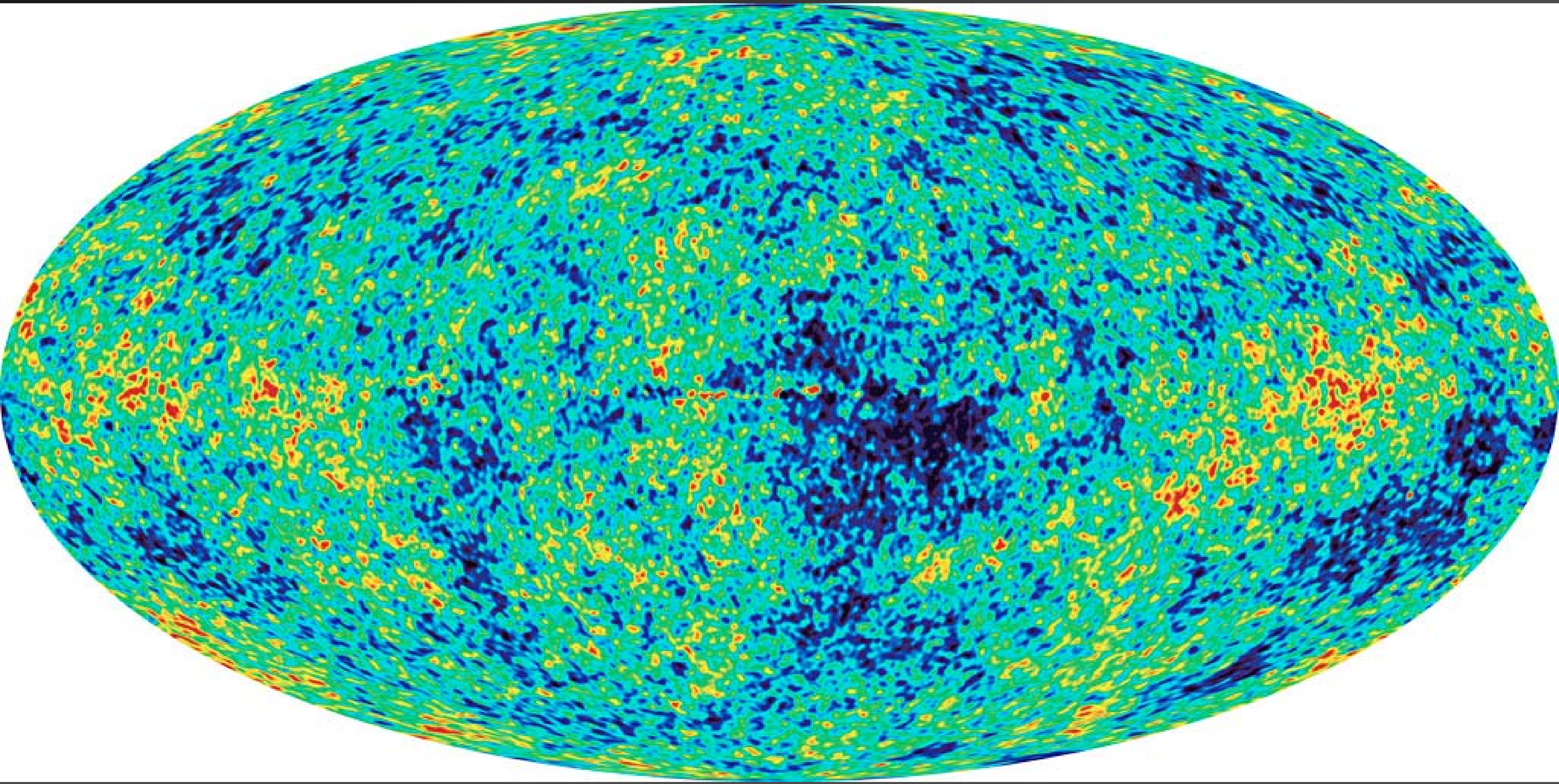
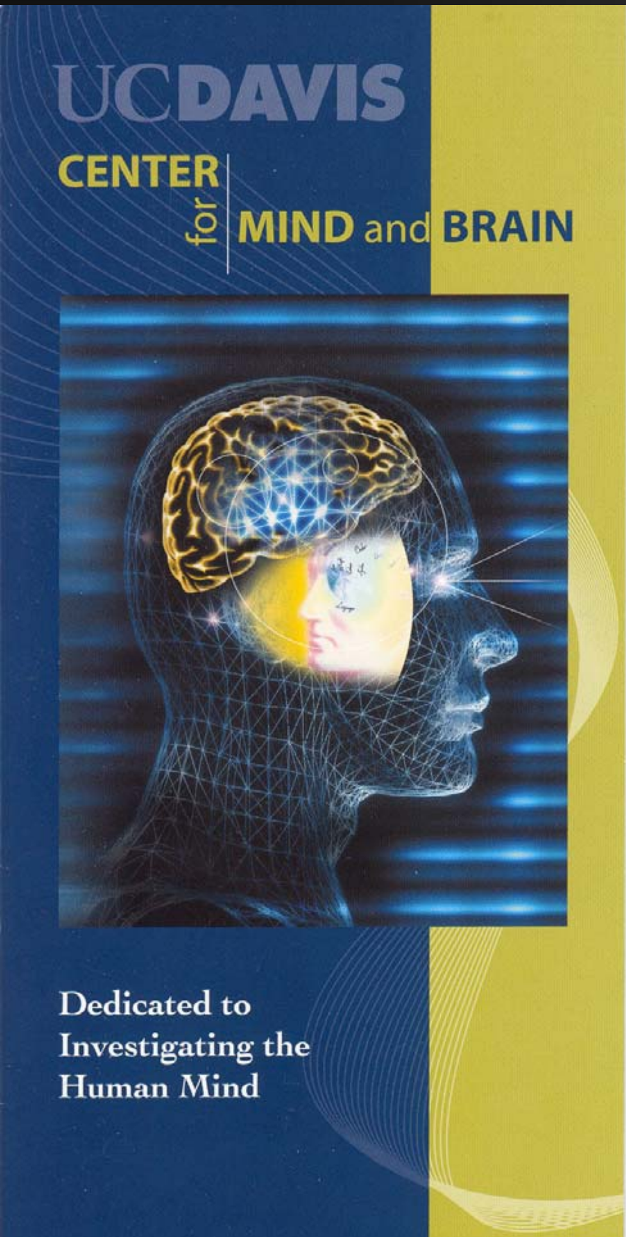
The WMAP map of the CMB



… a relic from a simpler era

The CMB: not only simple, but conveniently located.



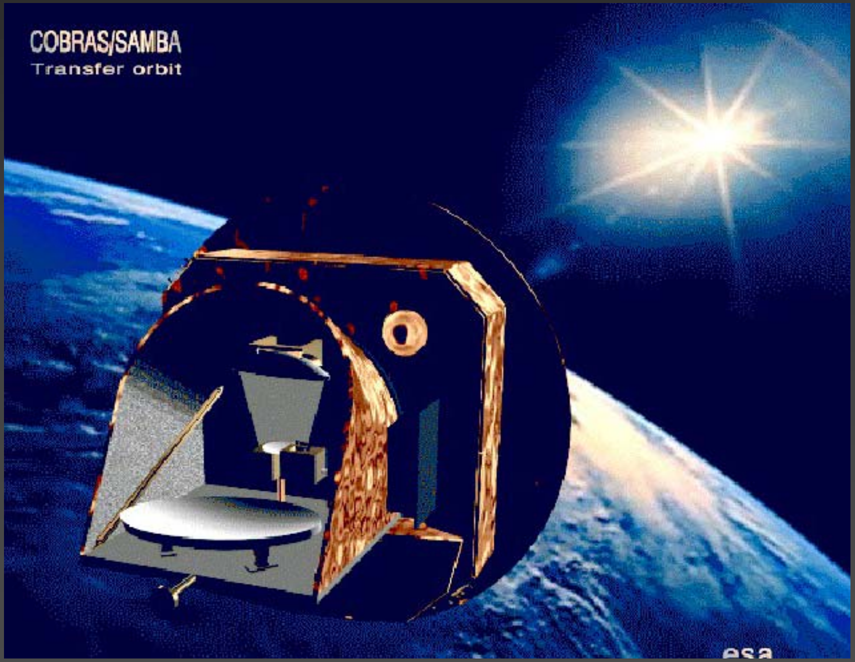
Facilities

The CMB is located just off the University of California campus in Davis. The 18,000 sq. ft. space was designed specifically with the needs of its faculty, students, staff and visitors in mind. Research facilities in the CMB include human electrophysiology labs containing 128 and 256 channel systems for

Beyond WMAP

QUAD, QUIET, PolarBEAR, SPT, ACT, APEX, Planck, CMBpol, …

- Inflation
- Reionization
- Gravitational Lensing
- Precision cosmological parameters



Planck (to be launched with Herschel)

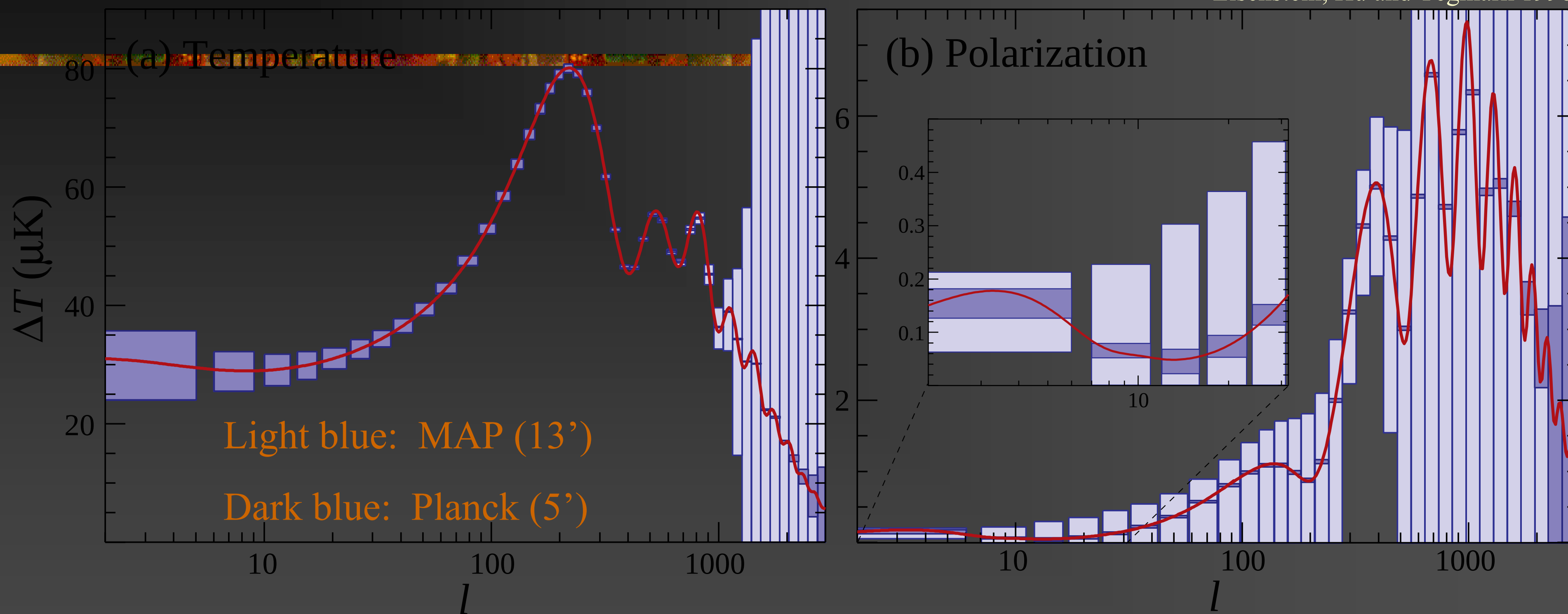
(improvement due to ang. res.)

Temperature

(improvement due to sensitivity)

Polarization

Eisenstein, Hu and Tegmark 1998



← Large angular scales

Small angular scales →

- P amplitude about 10% of T anisotropy
- l > 15 from last—scattering surface
- l < 15 from reionization

Why concentrate on 'Inflation'?

- Much more to learn about inflation from higher-resolution and higher sensitivity measurements of CMB temperature and polarization anisotropies, even if gravity waves are undetectably small.
- CMB is best observable for studying primordial fluctuations.
- The question of the origin of the seeds of all structure in the Universe is a pretty intriguing one. In fact… one worth having its own name…

BBI

(Big Bang Inhomogenesis)

Future CMB Measurements as Probes of BBI

- Extend to smaller angular scales to better measure power spectrum of primordial density perturbations, P(k)
- Search for non-Gaussianity
- Improve sensitivity of polarization measurements to go after gravity-wave signature in the polarization.

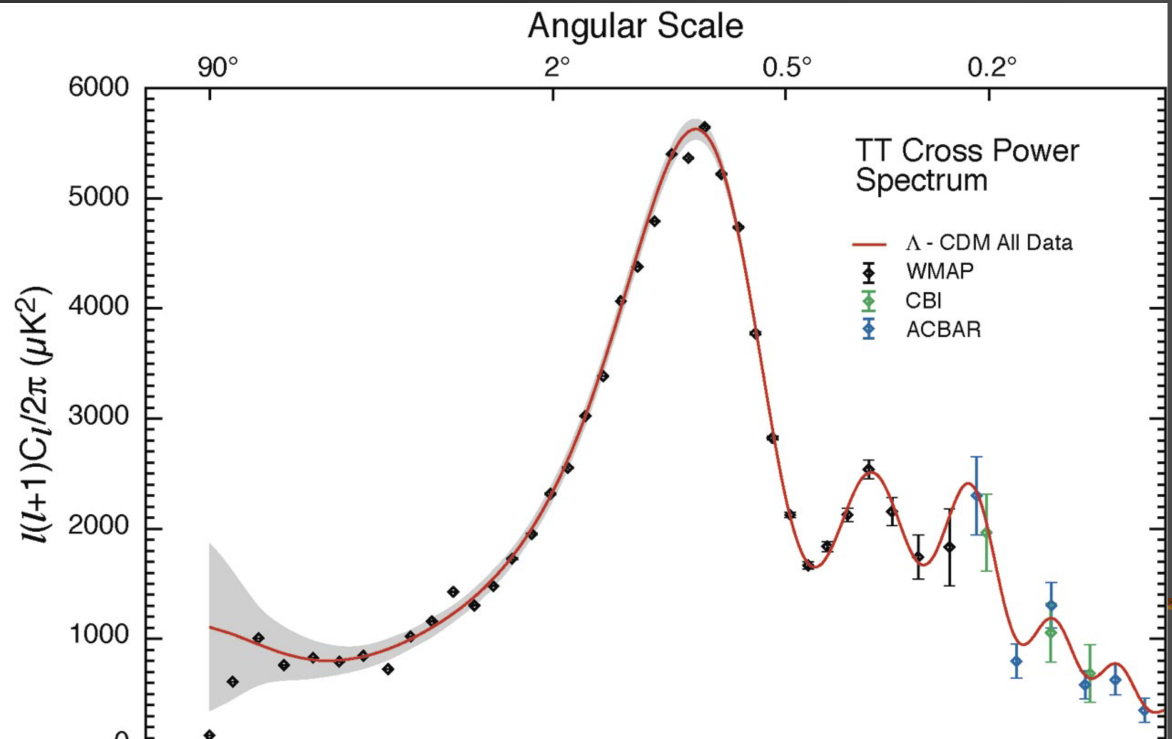
CMB constraints on primordial density perturbation power spectrum:

$$P(k) = A^2 k^{n_s(k)} \qquad n_s(k) = n_s(k_*) + ln(k/k_*) dn_s/dlnk$$

$$n_s(k_*) = 0.97 \pm 0.04$$

$$dn_s/dlnk = -0.077 \pm 0.05$$

Fluctuation Power



Forecasts of Parameter Errors

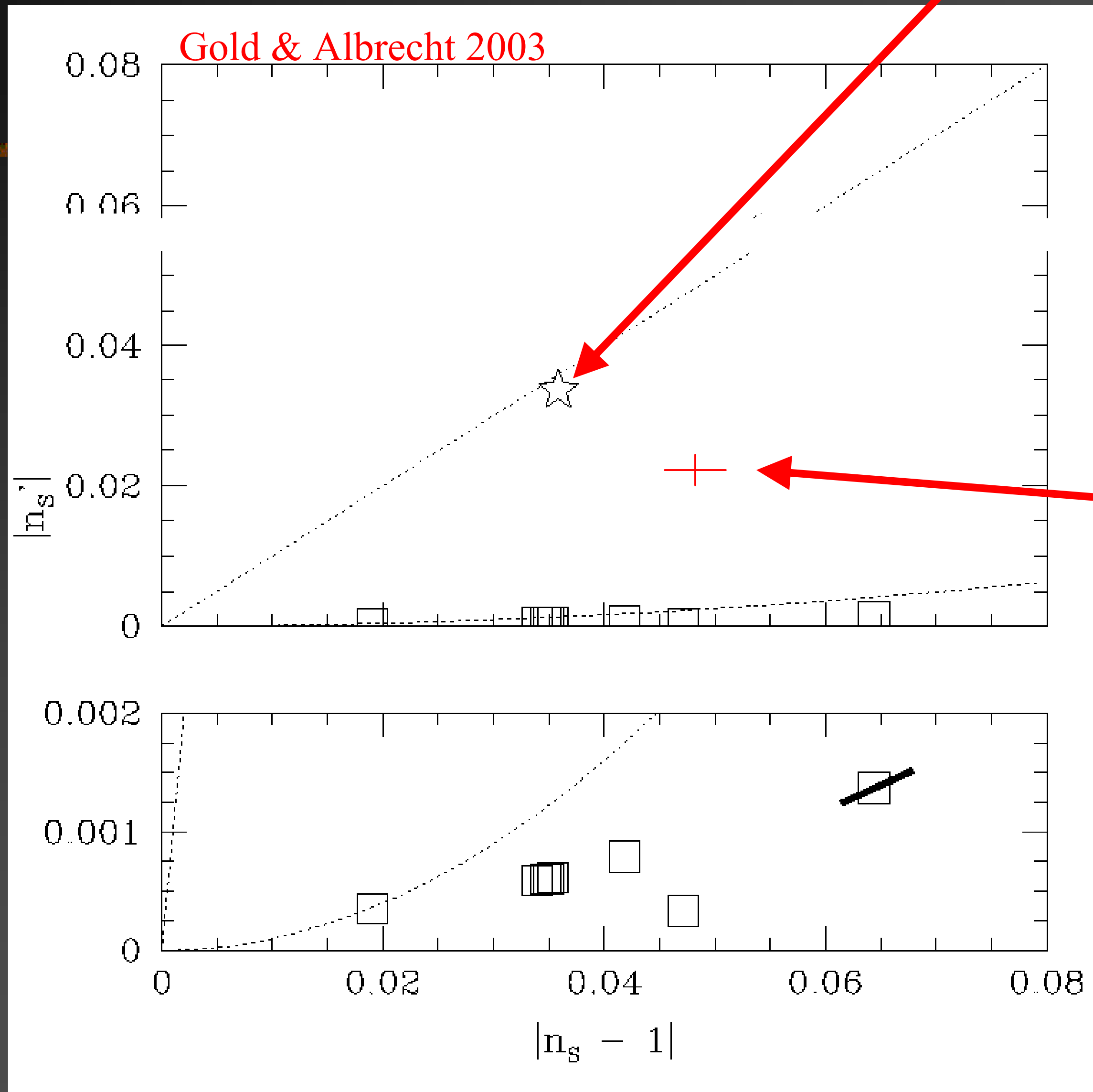
	n_s	$dn_s/d\ln k$	r (gravity waves)
WMAP	0.05	0.05	0.25
Planck (2007)	0.007	0.003	0.02
CMBpol (2016?)	0.003	0.0017	10^{-4}

Eisenstein et al. (1998) & Kaplinghat et al. (2003)

Inflation models

Designed to lie up here (Dodelson & Stewart 2002)

dn$_s$/dlnk



Forecasted size of CMBpol error

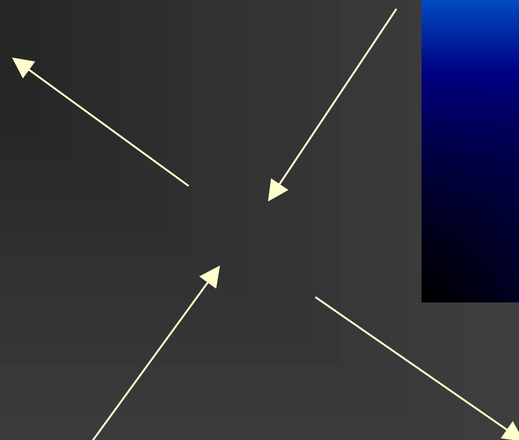
|n$_s$-1|

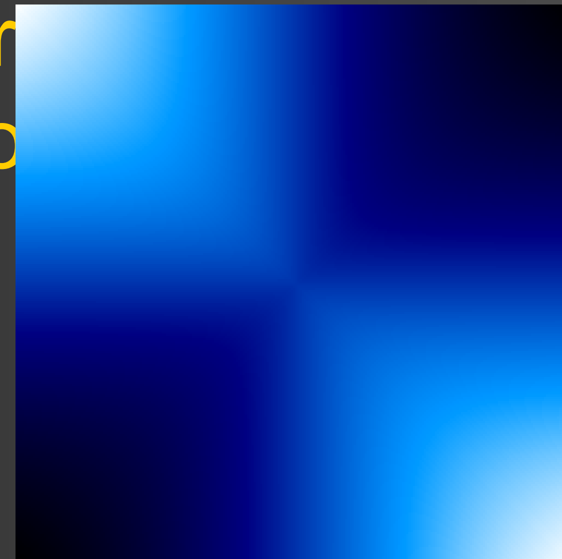
Tensor (gravitational wave) perturbations

- Power in gravity wave fluctuations directly tells us energy scale of inflation
- Gravity waves not predicted in cyclic model
- Unfortunately, gravity waves can be undetectably small in inflationary models.

Gravitational Wave Gener ure Anisotropy and Polarizatio

Imagine a single GW propagating out of the screen, compressing and stretching space as shown by arrows.

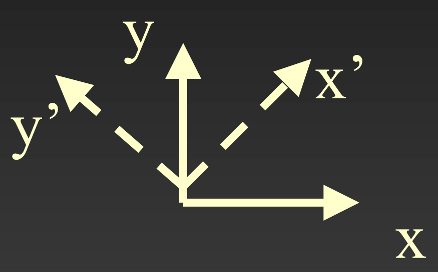




Resulting temperature pattern

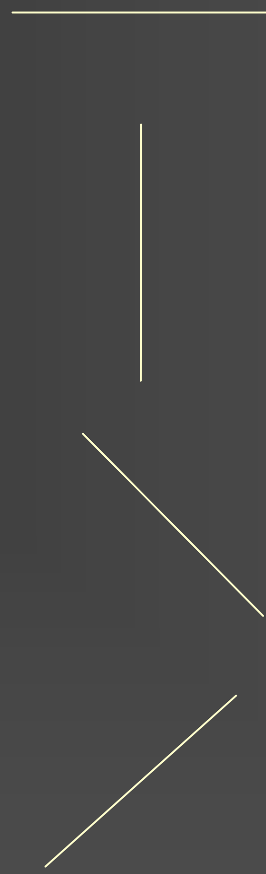
Also leads to polarization since unpolarized quadrupole radiation scattered by an electron results in polarization.

Polarization



$$Q = I_x - I_y$$

$$U = I_{x'} - I_{y'}$$



Q	U
+	0
-	0
0	-
0	+

E modes and B modes

Q can rotate into U but a Q wave is distinct from a U wave.

B modes not created by scalar (density) perturbations in linear perturbation theory

but they are created by tensor (gravitational wave) perturbations

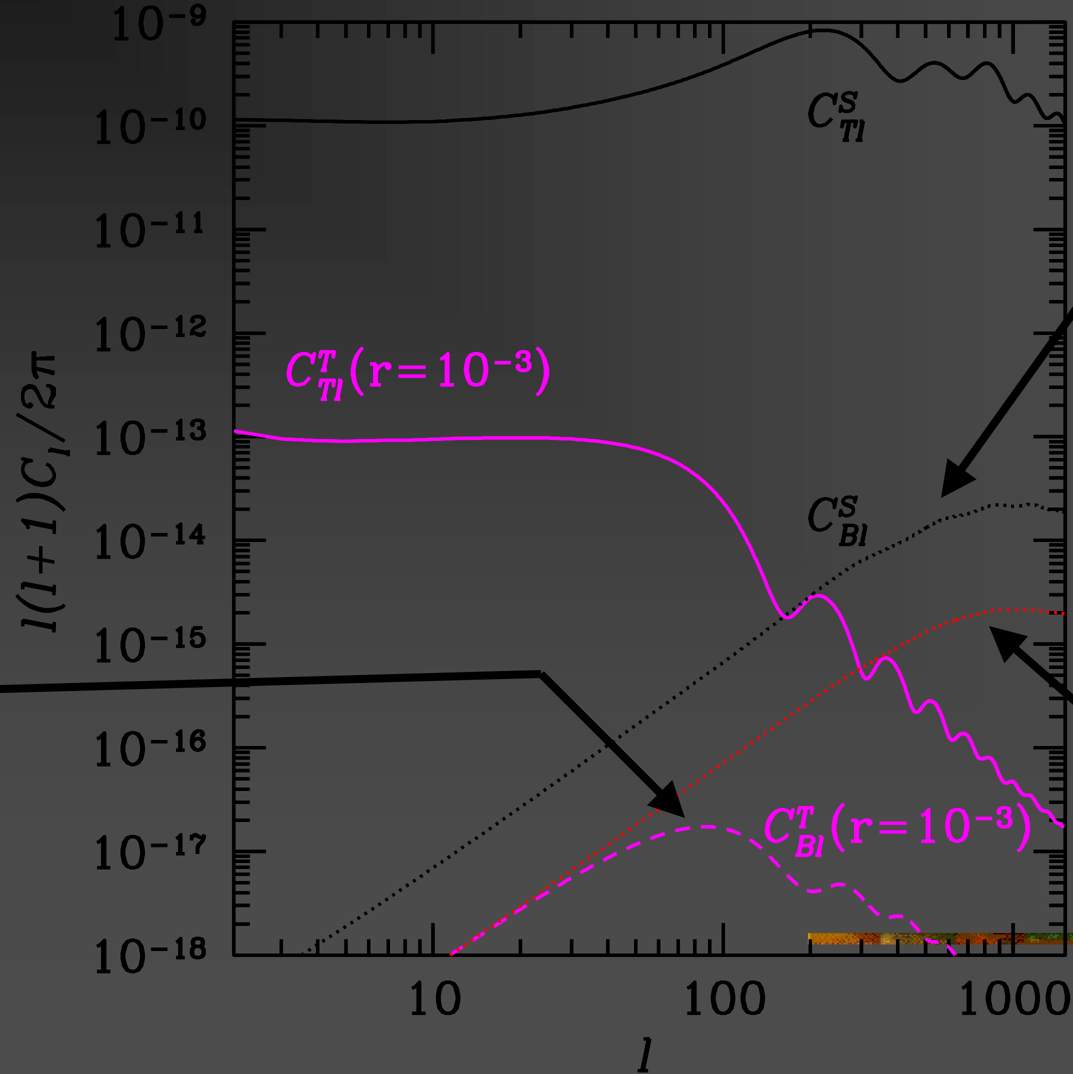
…and by lensing.

Knox and Song, astro-ph/0202286, and PRL

see also Kesden et al. astro-ph/0202434, and PRL and Hirata and Seljak (2003)

Detecting Tensor Perturbations

Hu and Okamoto, 2001 lensing potential reconstruction



Lensing—induced scalar B mode

The "B mode" polarization pattern is not generated by scalar perturbations in linear perturbation theory.

Residual scalar B mode power

Forecasts of Parameter Errors

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WMAP	0.05	0.05	0.25
Planck (2007)	0.007	0.003	0.02
CMBpol (2016?)	0.003	0.0017	10^{-4}

Energy scale of $\sim 10^{15}$ GeV

Eisenstein et al. (1998) & Kaplinghat et al. (2003)

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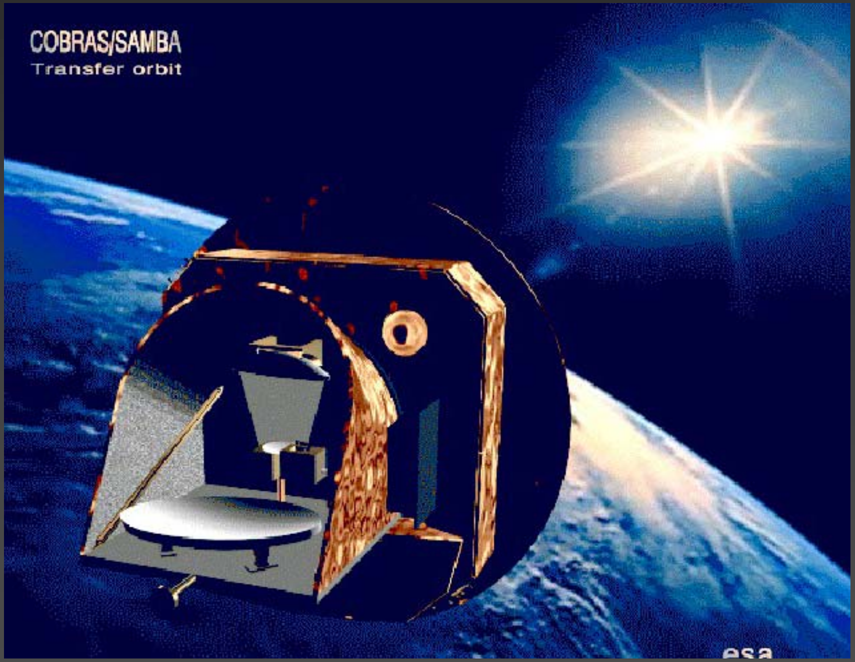
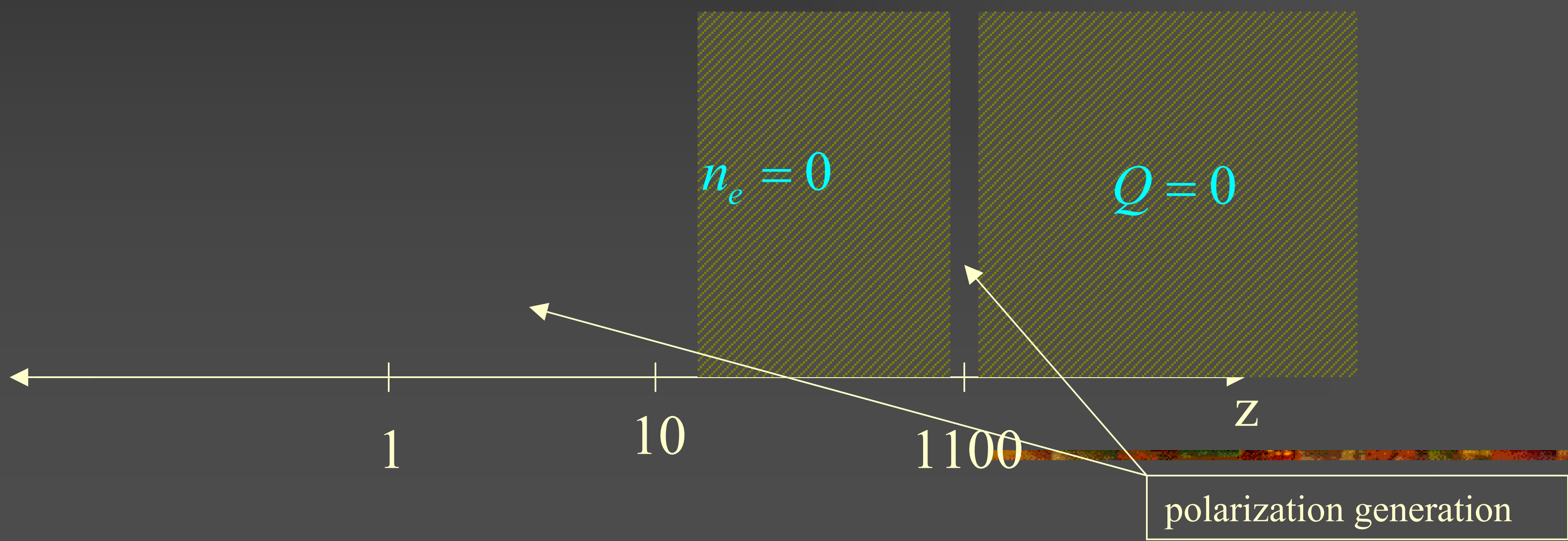


Planck (to be launched with Herschel)

CMB Polarization

Unpolarized radiation with a quadrupole moment scattering off of free electrons results in linearly polarized radiation.

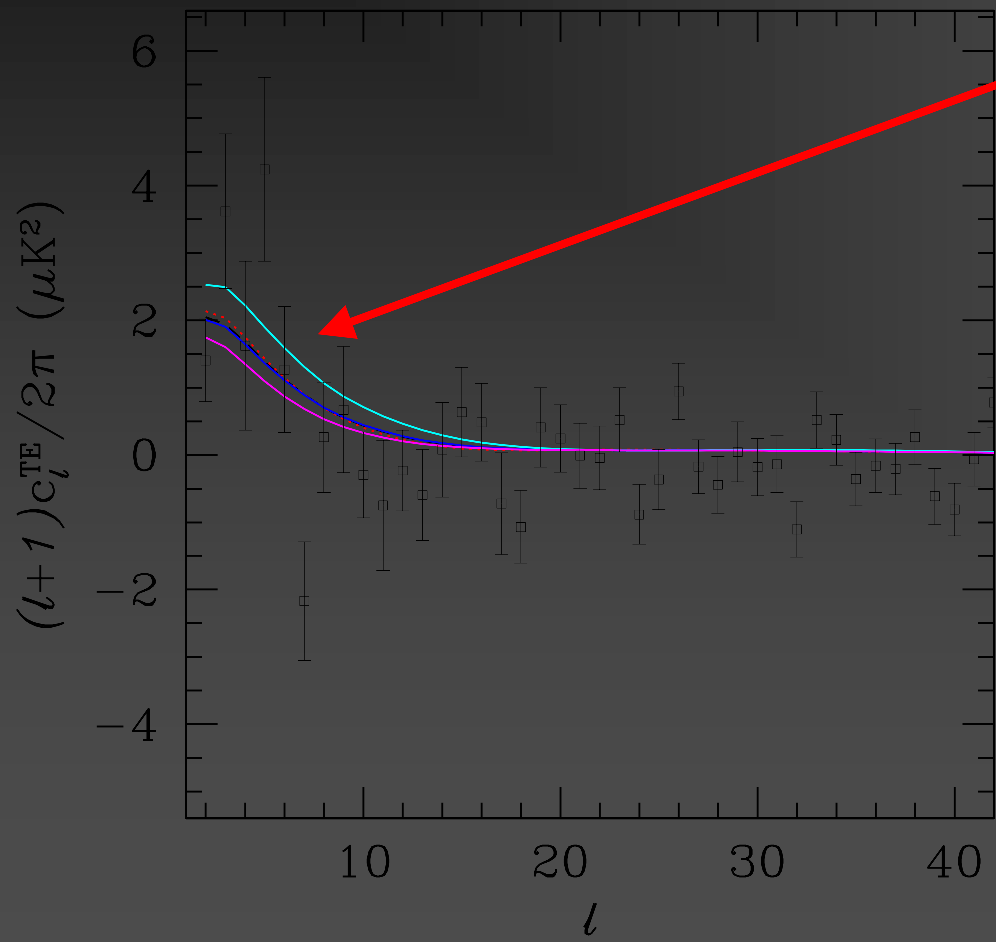
No Q at z > ~1100 (fast scattering isotropizes the radiation field)
No free electrons at ~17 < z < ~1100



Temperature-Polarization cross-correlation on large angular scales

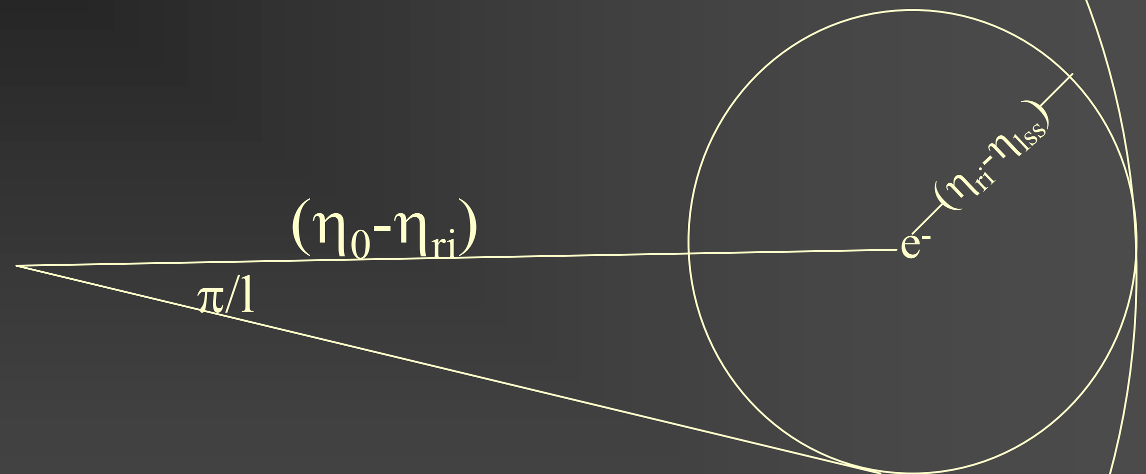
Holder et al. 2003

Data points from WMAP



Signal from reionization

The low l polarization bumps



$l=k(\eta_0-\eta_{ri})$

$2=k(\eta_{ri}-\eta_{lss})$

➔ $l=2\,(\eta_0-\eta_{ri})\,/(\eta_{ri}-\eta_{lss})$

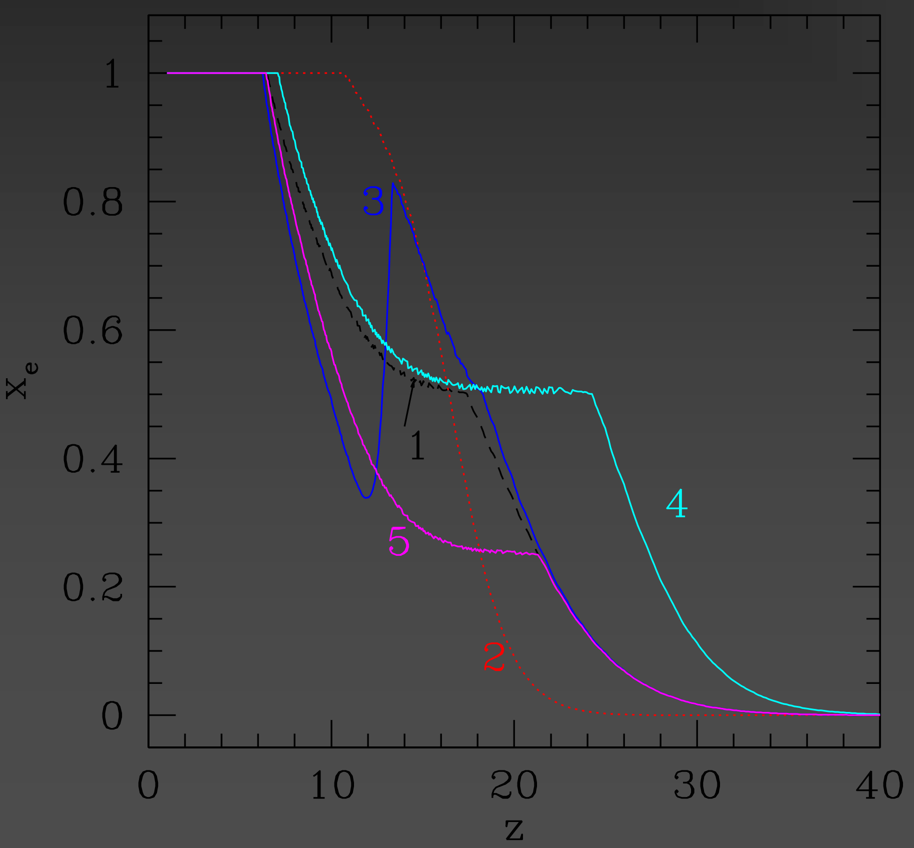
$C_l^{EE} \,/\, \tau^2$

$C_l^{TE} \,/\, \tau$

Zaldarriaga 97

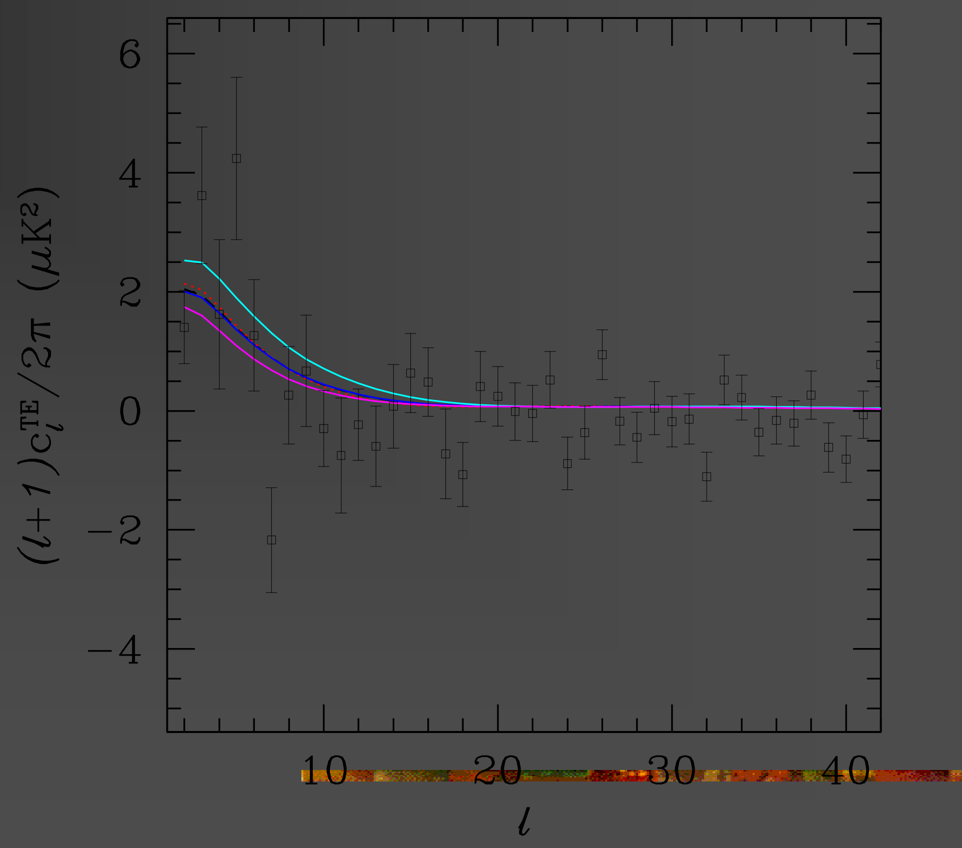
The Temperature-Polarization Cross Power Spectrum

Holder et al. 2003



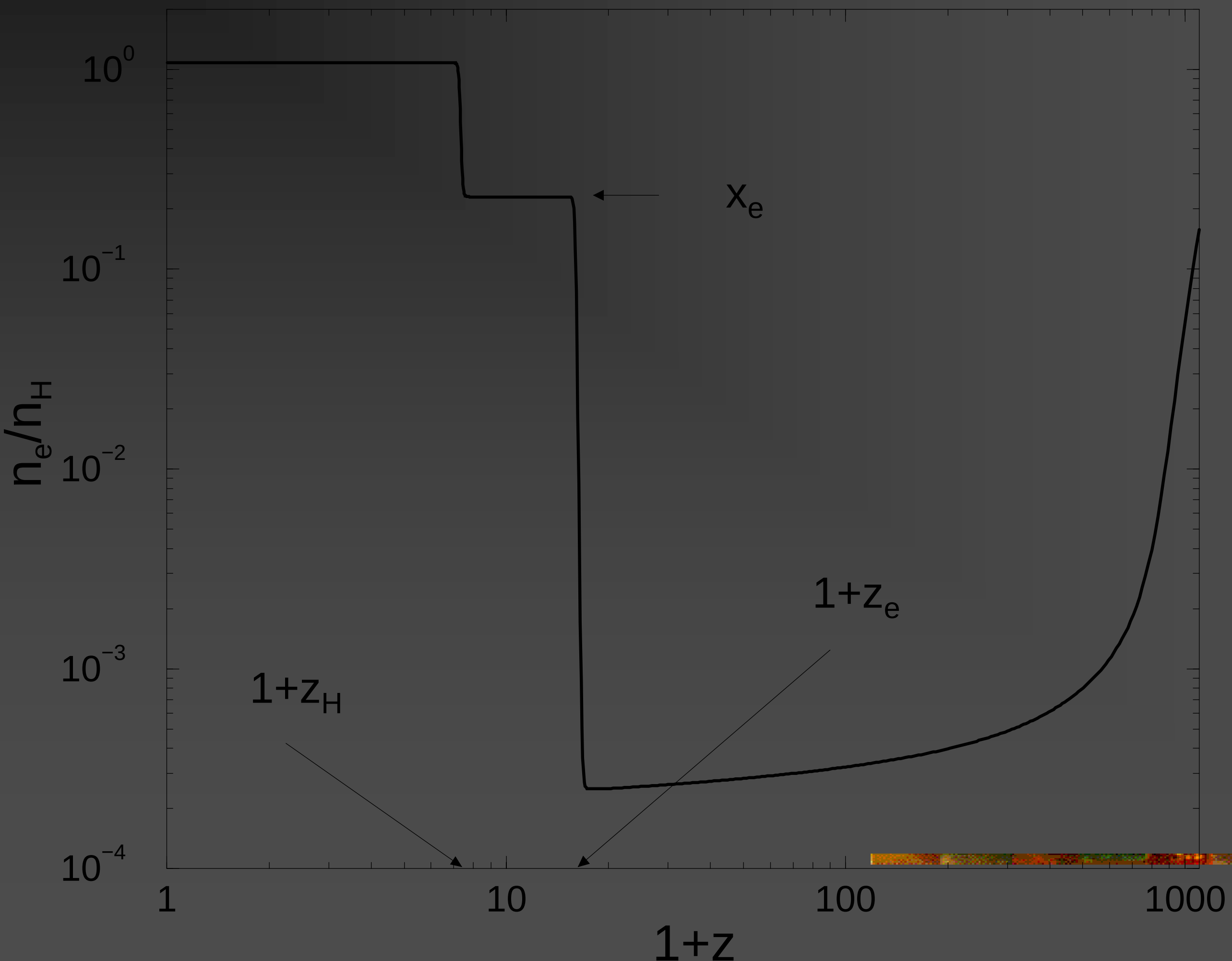
Holder et al. 2003

Data points from WMAP



Beyond τ

Kaplinghat et al. 2003

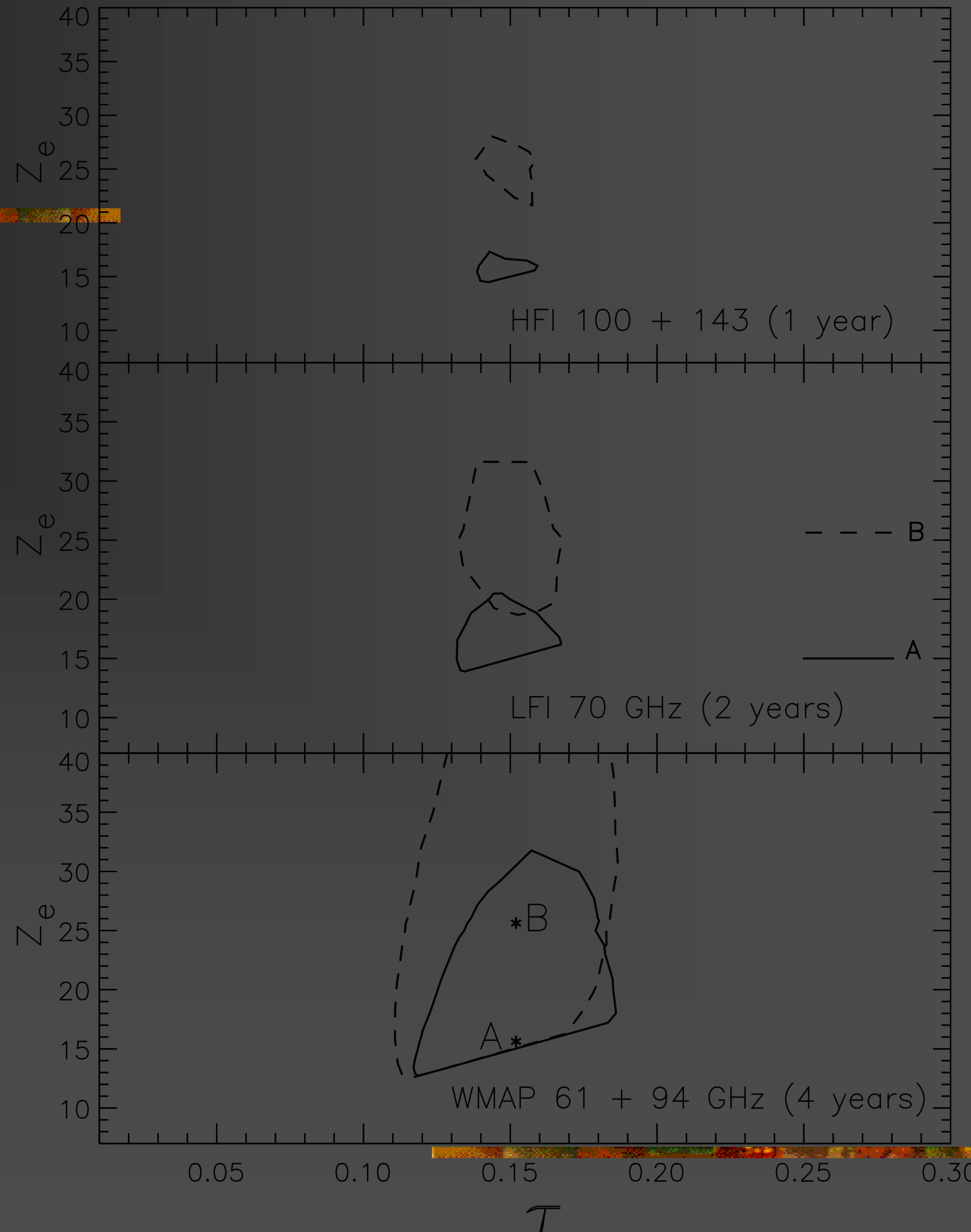


We will understand prospects better with 2-year WMAP data

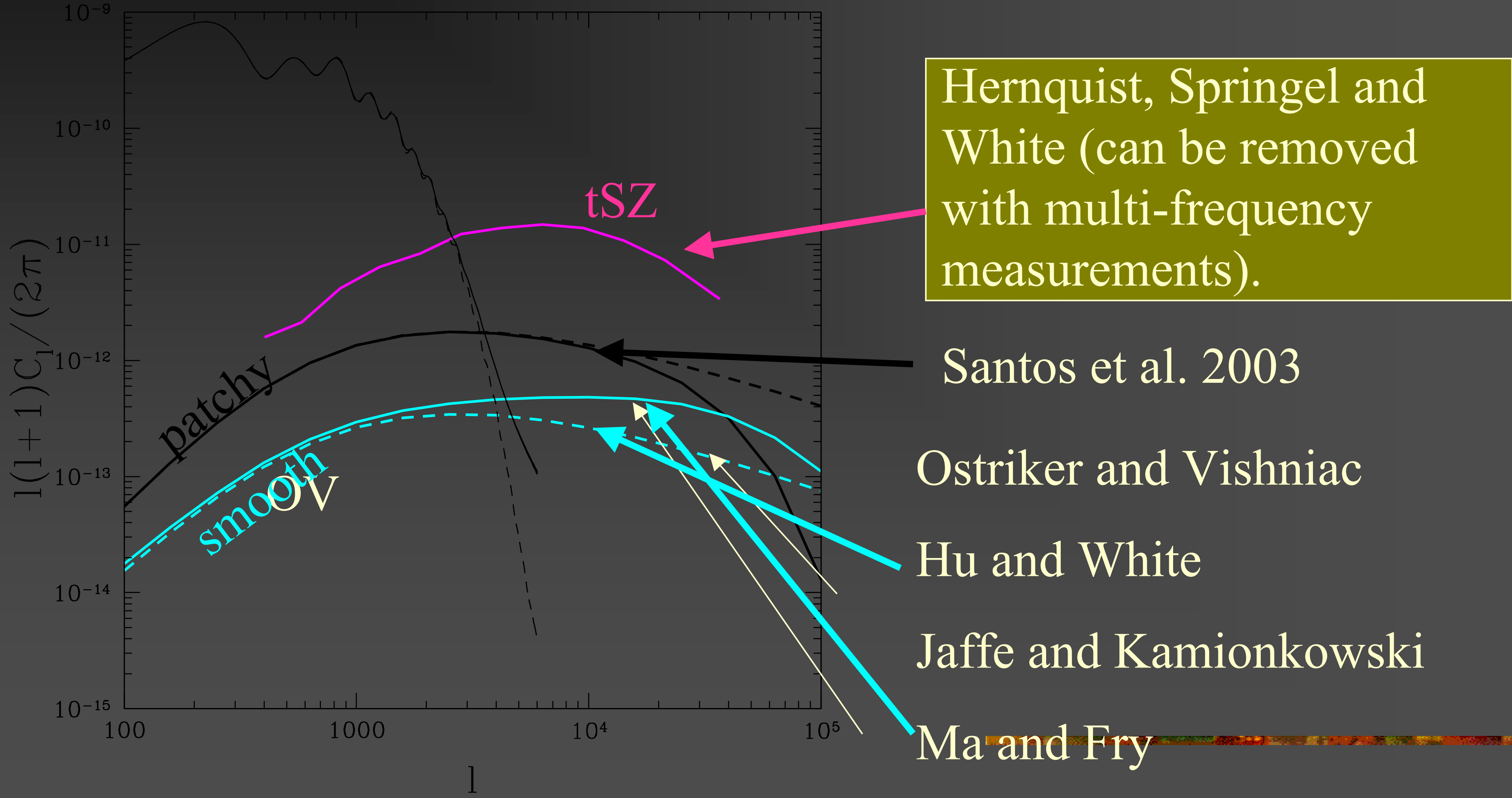
Beyond τ

68% confidence regions expected around two models with same optical depth.

Model A	Model B
z_e=25	z_e=16
x_e=0.58	x_e=1.08
τ=0.148	τ=0.148



Reionization signal on small scales: a target for ground-based experiments



Conclusions

- The question of the origin of structure is a profoundly important one.
- The CMB is our best observable for addressing this question.
- Orders of magnitude improvements in measurement of scalar and tensor primordial perturbation spectra are possible with future CMB missions.
- Much more science can be done than what I was able to cover in this talk (such as reionization… probably caused by first stars … which Volker Bromm will now talk about).

Detecting Gravitational Waves from Inflation

- Gravity waves create not just polarization E modes, but also B modes (which are not produced by density perturbations to first order).
- Gravity wave amplitude is proportional to expansion rate during inflation.
- ‘CMBpol’ is a possible future mission in NASA’s ‘Beyond Einstein’ probes with launch maybe in 2016.

Experimental Specifications for Forecasting

Kaplinghat, Knox & Song (2003)

Experiment	l^T_{max}	$l^{E,B}_{\mathrm{max}}$	ν (GHz)	θ_b	Δ_T	Δ_P
Planck	2000	3000	100	9.2'	5.5	∞
2007			143	7.1'	6	11
			217	5.0'	13	27
SPTpol ($f_{\mathrm{sky}} = 0.1$)	2000	3000	217	0.9'	12	17
CMBpol **2016?**	2000	3000	217	3.0'	1	1.4

$$w_x \equiv p_x/\rho_x$$

Nothing to write home about

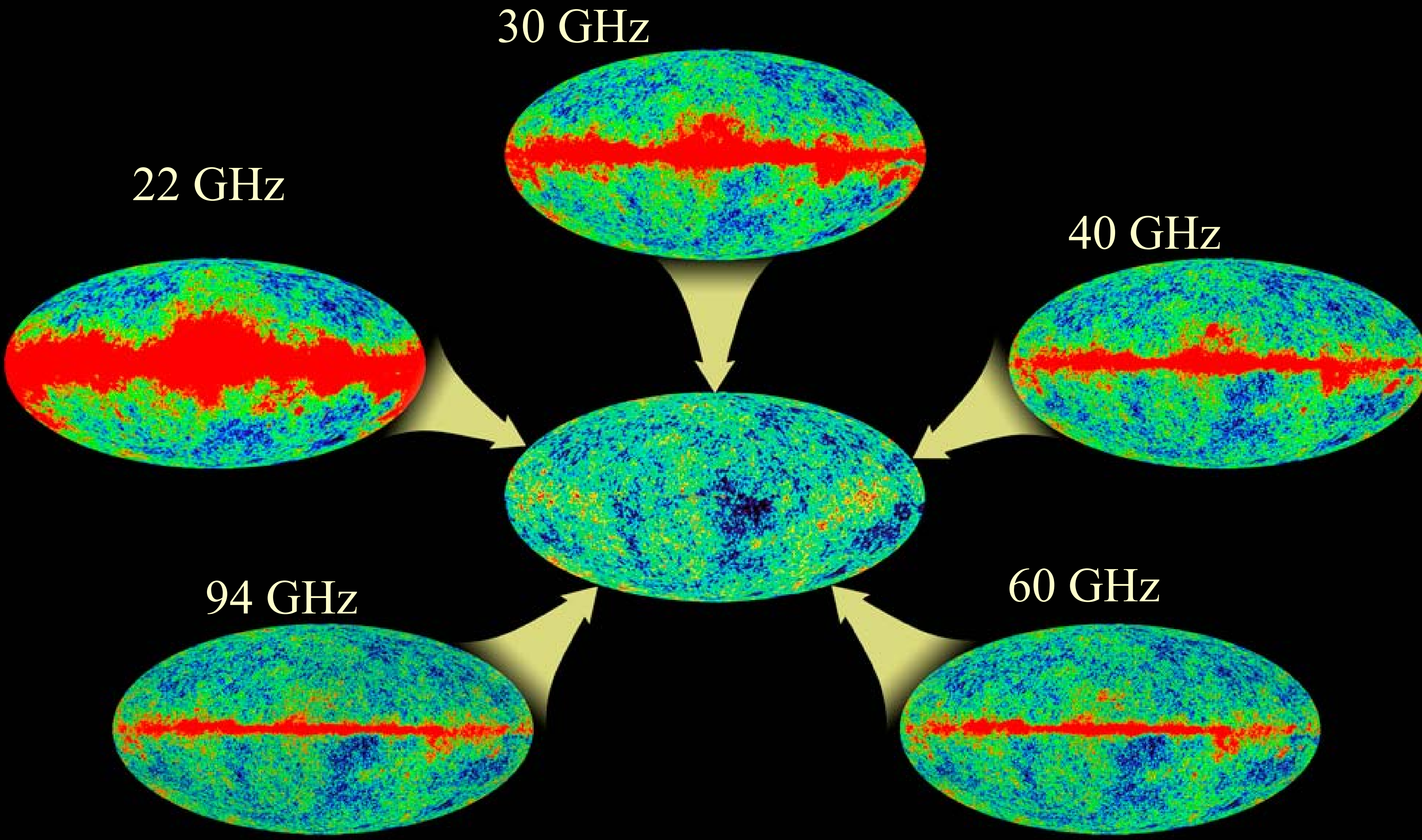
Parameter Error Forecasts

Kaplinghat, Knox and Song, 2003

Experiment	m_ν (eV)	w_x	n_S	n'_S
Planck	0.15	0.31	0.0071	0.0032
SPTpol	0.18	0.49	0.01	0.006
CMBpol	0.044	0.18	0.0029	0.0017

Interesting number given atmospheric neutrino oscillation constraint on Δm^2

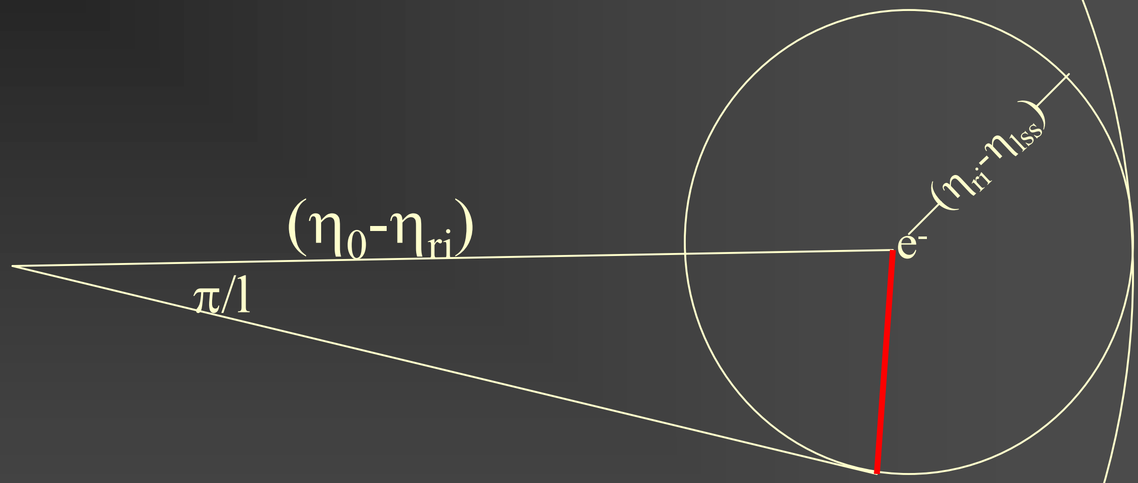
We would like to do a better job of constraining w.


30 GHz
22 GHz
40 GHz
94 GHz
60 GHz

What about Gaussianity?

- Prediction of simplest models of inflation: primordial density perturbations are a Gaussian random field (so completely specified by two-point correlation function)
- Three-point correlation function consistent with zero (Komatsu et al. 2003)
- But WMAP data departs from Gaussianity in other ways (Eriksen et al., Vielva et al., Larson & Wandelt)
- Is this truly primordial, instrumental effect, foreground contamination, …? Potentially profound implications for BBI. Must be followed up.

The low l polarization bumps



$2=k(\eta_{ri}-\eta_{lss})$

$l=k(\eta_0-\eta_{ri})$

$\rightarrow l_E=2\ (\eta_0-\eta_{ri})\ /(\eta_{ri}-\eta_{lss})$

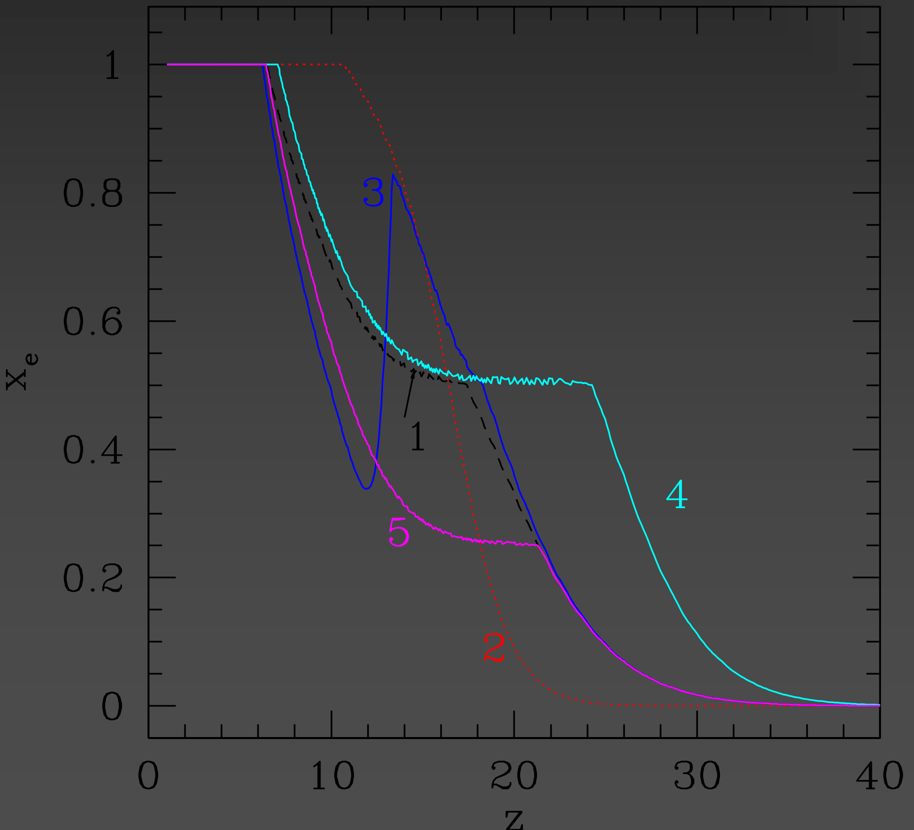
$\rightarrow l_T=2\ (\eta_0-\eta_{lss})/(\eta_{ri}-\eta_{lss})$

$C_l^{EE}\ /\ \tau^2$

$C_l^{TE}\ /\ \tau$

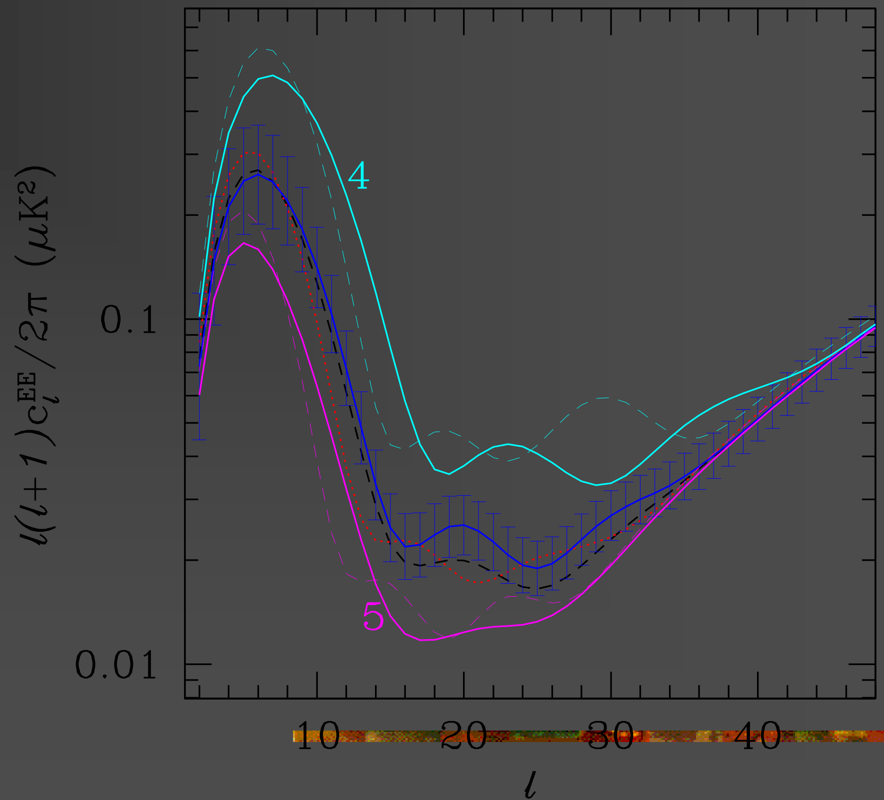
Reionization histories

Holder et al. 2003



The Pol-Pol power spectrum

Holder et al. 2003



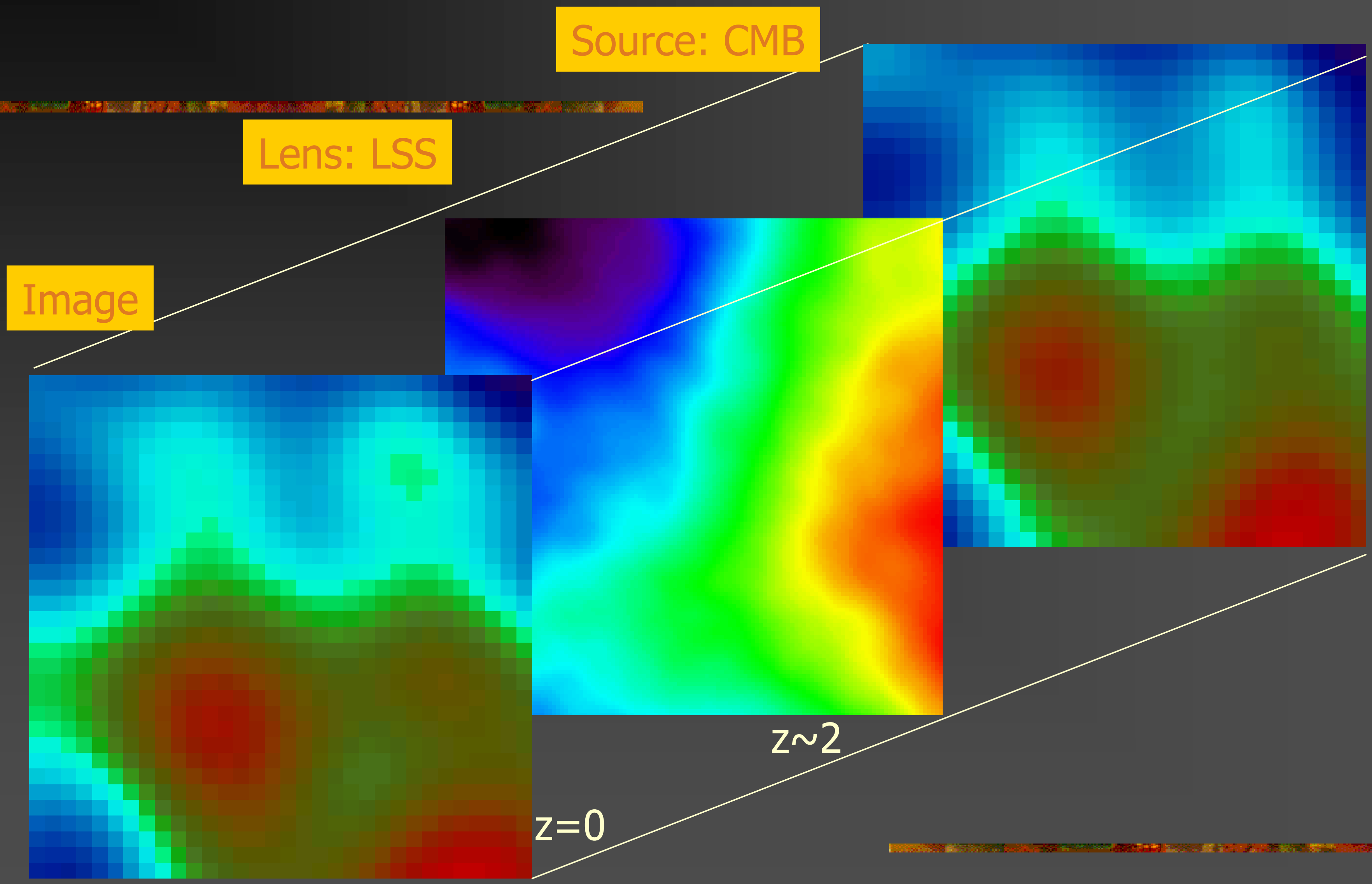
BBN and CMB Consistency Checks

- Determining ω_B, Y_P and N_ν to high precision will facilitate precision consistency tests between CMB and BBN.

- Given ω_B, a measurement of Y_P from the CMB can be translated into a measurement of N_ν at BBN such that $\sigma(N_\nu) = \sigma(Y_P)/0.013$ which for EPIC translates to $\sigma(N_\nu)$ ¼ 0.4.

- We can independently measure N_ν from the CMB. With EPIC it might be possible to go down to $\sigma(N_\nu)$=0.1.

Lensing of the CMB



WMAP and Power Spectrum of Density Fluctuations

$$k^3 P(k) = A(k/k_*)^{n_s(k)-1}$$

$$n_s(k) = n_s(k_*) + dn_s/dlnk \ln(k/k_*$$

- n_s = 0.97 § 0.04 (6 parameter model)
- n_s = 1.20 § 0.11 (allow gravity waves and $dn_s/dlnk$ non-zero)
- $dn_s/dlnk$ = -0.077 § 0.05
- r < 1.28 (95% confidence)

Peiris et al. 2003 & Spergel et al. 2003